HIGH CURRENT, MULTI-FILAMENT PHOTOCONDUCTIVE SEMICONDUCTOR SWITCHING [*]

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Abstract

High current switching is the most critical challenge remaining for photoconductive semiconductor switch (PCSS) applications in Pulsed Power. Many authors have described the advantageous properties of high gain PCSS such as, low optical trigger energy and inductance, sub-nanosecond risetime and jitter, optical isolation and control, pulsed or DC charging, and long device lifetime, provided the current per filament is limited to 20-30A for short pulse (10-20ns) applications[1,2]. Low energy optical triggering, long device lifetime, and current filaments are related features of high gain PCSS that make high current switching a challenge. Since the location and number of current filaments can be controlled with parallel "lines" of optical pulses across the insulating gap, the problem of high current, multi-filament PCSS switching is essentially the problem of producing a reliable, efficient, multi-line, optical delivery system[3].

In this paper, several classes of optical delivery systems will be discussed: line-of-sight plastic and glass micro-lens arrays, multi-mode fiber-optic/micro-lens combinations, single-mode fiber-optic/micro-lens array combinations, and masked PCSS alone and with other optical "concentrating" components. The application dependent advantages and disadvantages of each approach will be discussed. Results will be shown from specific examples (plastic and glass micro-lens arrays, single and multi-mode fibers and bundles, and high density optically masked PCSS) that have been tested and demonstrated.

The fundamental requirements of multi-filament, high gain PCSS triggering are also being measured and will be reported. Optical trigger energy, pulse width, line-width, and spatial density are the key factors in determining the attainable switching efficiency and volume for high current pulsed power applications. Measurements of these properties and their implied trade-offs will be presented.

A high voltage, high current, high gain PCSS demonstration will be described. In these tests, three 1 cm gap PCSS switch a 60 KV Blumlein conducting 2.5 kA for 6 ns with approximately 100 filaments spaced at 30 filaments/cm. This system will test the practical aspects of optical triggering with the line-of-sight micro-lens and masked PCSS approaches. Along with these results, we will also discuss our plans to demonstrate 100 kV, 25 kA, 1000 filament switching with a bank of PCSS.

I. INTRODUCTION

Pulsed power systems continue to evolve towards greater complexity, lower impedance, and more precise control[4,5,6,7]. For pulse shaping and short pulse systems, precision switch timing is critical. The ability to produce these systems is dependent on the types and qualities of the dielectrics, the quality of the control system and triggering, and the performance of the switches. In systems such as Genesis[8], the performance of the switch is key to the quality of the shaped pulse output. Performance of the gas switches evaluated for Genesis, and any system operated similar to Genesis, is limited by the changing fields resulting in changing runtimes and jitter. PCSSs overcome this limitation due to the different mechanism used to control the switch. The performance of the PCSS is consistent across a large range of fields from twice the lock-on field of approximately 10 kV/cm to the maximum operating field of approximately 70 kV/cm in pulse charged operation[9]. This along with the ability to control the triggering of the PCSS devices to within 100 ps rms jitter[10], makes these switches ideal for high performance applications. The limiting characteristic of PCSS devices in many of these applications has been the significant reduction in lifetime as the filament current increases above 30 A[11]. This research addresses this limitation by seeking methods to efficiently and reliably generate large numbers of current-sharing, linear filaments on a single PCSS. One approach to multi-filament high gain PCSS triggering is to form lines of light across the PCSS with the trigger laser or lasers and a suitable optical delivery system[3]. This approach results in the creation of multiple, current-sharing, linear filaments along the lines of the light. This can be very efficient, since each line of light can be formed with microjoules of optical energy and an efficient optical delivery system will not waste a large amount of trigger energy. However, this approach requires additional optical components and alignment procedures. In some systems, where the laser energy requirement is not a major issue, this extra hardware and maintenance may not be a desirable feature of the design. A simpler and less labor-intensive approach to form multiple, current-sharing, linear filaments, is to mask the regions on the PCSS where filaments should not form. Uniform illumination of a masked switch with unmasked lines crossing the insulating gap will produce multiple, linear,

[*] Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. Funding for part of this research was also provided by the Defense Threat Reduction Agency.

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Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUN 2011**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **High Current, Multi-Filament Photoconductive Semiconductor Switching**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Army Research Laboratory, 2800 Powder Mill Road Adelphi, MD 20783 USA**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. IEEE International Pulsed Power Conference (19th). Held in San Francisco, CA on 16-21 June 2013., The original document contains color images.

14. ABSTRACT

High current switching is the most critical challenge remaining for photoconductive semiconductor switch (PCSS) applications in Pulsed Power. Many authors have described the advantageous properties of high gain PCSS such as, low optical trigger energy and inductance, sub-nanosecond risetime and jitter, optical isolation and control, pulsed or DC charging, and long device lifetime, provided the current per filament is limited to 20-30A for short pulse (10-20ns) applications[1,2]. Low energy optical triggering, long device lifetime, and current filaments are related features of high gain PCSS that make high current switching a challenge. Since the location and number of current filaments can be controlled with parallel lines of optical pulses across the insulating gap, the problem of high current, multi-filament PCSS switching is essentially the problem of producing a reliable, efficient, multi-line, optical delivery system[3 In this paper, several classes of optical delivery systems will be discussed: line-of-sight plastic and glass micro-lens arrays, multi-mode fiber-optic/micro-lens combinations, single-mode fiber-optic/micro-lens array combinations, and masked PCSS alone and with other optical concentrating components. The application dependent advantages and disadvantages of each approach will be discussed. Results will be shown from specific examples (plastic and glass micro-lens arrays, single and multi-mode fibers and bundles, and high density optically masked PCSS) that have been tested and demonstrated.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

current-sharing filaments at a selectable line density. The trade-off with this approach is a significant increase in the laser energy requirement. With a masked switch, most of the optical trigger energy will be deposited on the masked regions between the filaments, which will typically be much wider than the unmasked lines to avoid intersecting, non-uniform current-sharing filament formation.

II. HIGH GAIN VERSUS LINEAR PCSS

A diagram of a generic PCSS is shown in figure 1. In a "linear" PCSS, one electron-hole (e-h) pair is produced for almost every photon that is absorbed. The quantum efficiency for e-h pair production with above bandgap radiation is close to 1. As linear PCSS are enlarged to stand-off higher voltages, the optical trigger energy required to reach the same on-state resistance increases with the square of the switch gap length or voltage hold-off strength. More photons are required to cover the increased length and a higher density of photons is required to increase the conductivity and obtain the same on-state resistance. Since pulsed power systems typically deal with very high voltages, they require very large PCSS and correspondingly linear high voltage PCSS require very large trigger energies. A linear PCSS typically requires ~50 mJ to switch a 100 kV charged circuit into a 50 ohm load (PCSS on-resistance to 1 ohm).

In GaAs and other direct bandgap semiconductors such as InP, avalanche carrier generation occurs at surprisingly low fields (4-6 kV/cm in GaAs, a). This avalanche carrier generation field has been measured and verified by many authors, however, the process has only been successfully described by qualitative models which predict higher fields with the closest prediction being a factor of ten larger than the field that is observed[12,13]. When a GaAs PCSS is triggered above the avalanche carrier generation field, additional e-h pairs are generated by the electric field.

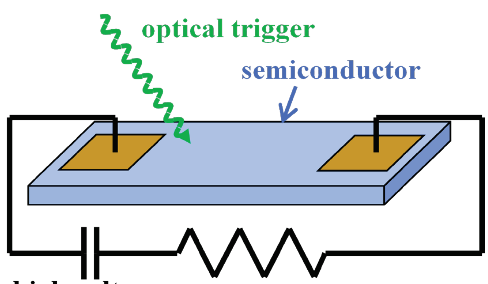

Figure 1. A generic photoconductive semiconductor switch rapidly discharges a charged capacitor or transmission line when photo-carriers change the resistance of the semiconductor from megaohms to milliohms as a trigger laser pulse is absorbed in the insulating gap. The conductivity of the switch increases linearly with the time integral of the laser pulse.

When the field across the switch drops below the avalanche field, the carriers re-combine with recombination times that depend on the impurities and defects in the GaAs. The longest recombination times are 10-20 ns and the shortest are a few picoseconds in low temperature grown or neutron irradiated GaAs. Avalanche carrier generation has three important effects in PCSS. (1) The on-state voltage across the switch balances to a constant value, often called the "lock-on voltage". (2) The energy required to trigger the switch is reduced by many orders of magnitude due to the extra carriers generated by the electric field. (3) The current from avalanche carrier generation forms into filaments which must be limited in amplitude and duration to avoid damaging the semiconductor switch. In low impedance (sub-ohm) circuits the extra carrier "gain" can be as high as 10^5 carriers per incident photon or photo-carrier. So there is a large potential savings in the optical trigger energy required to trigger a high gain PCSS. Typical high gain GaAs PCSS that can hold-off 100 kV require ~1μJ to trigger into high gain switching. However, if the high gain PCSS is driving a 50 ohm load, it would require 100 filaments or ~100 μJ to conduct 2 kA for ~20 ns without damaging the PCSS[14]. A trigger energy savings of ~500 would be available in this example, but the current must be shared by multiple filaments, which requires a more complicated optical delivery system than a linear PCSS. Optical delivery systems for multiple, current-sharing, linear filaments are the subject of this research.

There are many issues with high gain PCSS which will be described briefly in the next section. Linear PCSS, in turn, have many virtues, despite their increased trigger energy requirement at high voltages. When triggered with a short pulse laser, linear PCSS have extremely high bandwidth. Figure 2 shows a linear PCSS based cable pulser driving a 50 Ohm 12 GHz Transverse electro-magnetic (GTEM) cell. A 100 fs laser pulse was used to trigger the switch with 19 μJ.

Figure 3 displays the voltage pulse delivered to the GTEM. Its risetime was limited by the bandwidth of the transmission lines (HN), the switch cavity, and the connectors, to 34 ps. The maximum charge voltage was limited to 2 kV by the potential breakdown strength of the

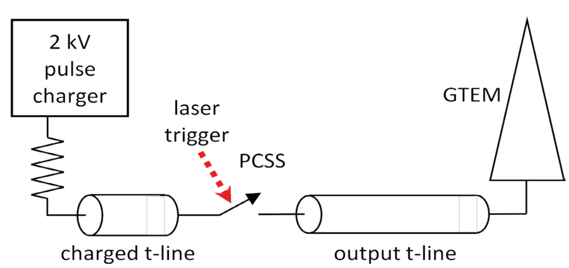

Figure 2. A charged transmission line is switched to a 12 GHz TEM cell with a linear PCSS triggered with a 100 fs laser pulse.

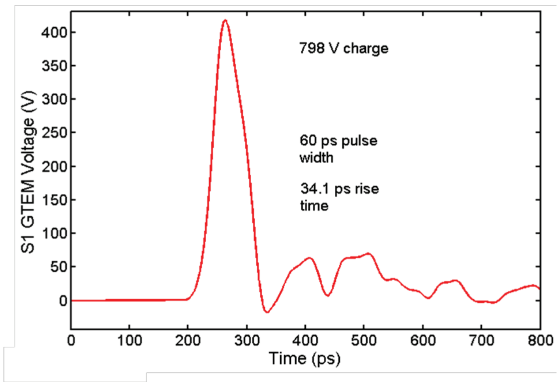

Figure 3. The voltage pulse delivered to the GTEM cell in the previous figure.

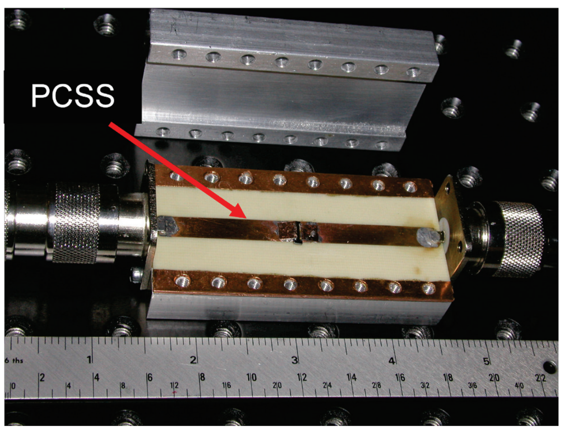

Figure 4. A picture of the 1 mm gap PCSS mounted in its 50 ohm cavity between the transmission lines.

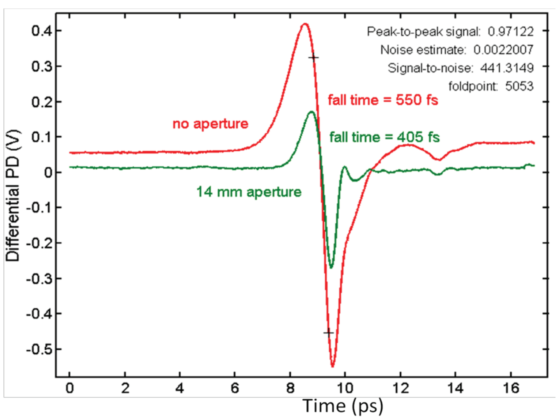

Figure 5. A plot of the radiated waveform from a 2.5 mm PCSS triggered with a 10 μJ, 100 fs laser pulse.

HN cable connectors. A picture of the PCSS in the holder between two 50 Ohm strip lines is shown in Figure 4.

Even higher bandwidth is demonstrated when a linear PCSS is used to radiate a pulse instead of transmitting it down a bandwidth limiting transmission line. Linear PCSS are a common source of pulsed THz radiation. Figure 5 shows the temporal waveform from a GaAs PCSS triggered with a 100 fs laser pulse measured with electro-optic sampling. The 400 fs risetime shown in this plot is limit by the dispersion and path length variation in the electro-optic crystal. Reducing the aperture of the receiver reduced the path length variation in the electro-optic crystal and increased the diagnostic bandwidth.

III. HIGH GAIN PCSS PROPERTIES

Except for high current, most of the switching properties of high gain PCSS have been tested and developed to the point of useful, reliable, and practical operation. Table I lists many of these properties that have been demonstrated over the last twenty years. These properties are very competitive with other pulsed power (high voltage) switch technologies. Risetime and jitter are not as good as linear switching where they are essentially zero (< 1ps) , but they are still clearly better than other pulsed power switch technologies which are a few nanoseconds at best and longer for low impedance circuits due to higher switch inductance.

Table I. High Gain GaAs PCSS Properties [3,9-11,15] (not simultaneous)

Voltage:	210 kV
Current:	8 kA
Peak Power:	780 MW
Electric Field (1 cm):	80 kVDC/cm (n-irrad.)
Electric Field (1 cm):	50 kVDC/cm (not irrad.)
Electric Field (1 cm):	70 kV/cm (100 μs)
Electric Field (1 mm):	100 kV/cm (100 μs)
Risetime:	370 ps
Trigger Energy (1 mm):	2 nJ
Trigger Energy (2.5 mm):	12 nJ
Trigger Energy (1 cm):	500 nJ
R-M-S Jitter:	<50 ps
Rep. Rate:	10 kHz
Device Life (20 A, 20 ns):	>1e8 pulses

The 8 kA current listed in this table was obtained by triggering multiple linear filaments through 180 cylindrical 1 mm diameter glass rods on the surface of six 2-inch diameter GaAs wafers. A 3 mJ uniform optical pulse was delivered to these cylindrical lenses in 192 multi-mode fibers (200 micron dia., 15 μJ/fiber)[3]. This was a monumental effort that made it clear a better approach was needed to reach typical pulsed power currents of 100 kA to 5 MA which would require 5,000 to 250, 000 filaments to avoid damage to the high gain PCSS. If stacked banks of PCSS are also required to get high voltages (e.g. 5 MV would require fifty 100 kV banks), then each of these banks would require the number of filaments stated above implying a total of 250,000 to 12,500,000 filaments. Although this is an extreme number of filaments, the optical trigger energy required (at 1μJ /filament) would only be 12 J, which for a machine the size of SATURN is not an excessive amount of energy. Indeed, the energy switched by these filaments, 5 MV and 5 MA for 20 ns would be 500 kJ.

Since the other properties in table I are readily achievable with reasonably sized, relatively low cost GaAs PCSS, the "missing link" to useful, practical, and reliable high gain PCSS switching for large pulsed power applications is an optical delivery system that will initiate thousands to millions of current sharing, linear filaments. With the technological tools available today, such an optical delivery system is not beyond achievement. In fact, the biggest issue may be determining which of the many possible approaches is best for each application. For many systems, one can envision a modular approach that delivers precisely aligned optical components and GaAs PCSS in reliable high voltage compatible packages.

IV. FILAMENT FORMATION

Filaments in HG GaAs PCSS are easily observed, because the high carrier density regions emit bandgap radiation as the e-h pairs recombine. The wavelength of GaAs bandgap radiation is centered on 875 nm, which can be recorded by silicon cameras that are very sensitive in this wavelength regime if they do not have near IR correcting filters. Since the filament formation and current conduction only lasts for 1-100 ns, these cameras capture open shutter pictures of the filaments in a single frame or field if their outputs are interlaced[16]. Figures 6 and 7 show examples of filaments, during high gain switching under the same conditions. Similar to images of lightning, the filaments created with uniform or spot triggering are different on every shot. The bright and dark branched structure indicates that the current is not uniformly distributed. The total current conducted by these filaments is plotted in figure 8. High current or long pulse filaments typically damage the PCSS near the contacts, where for even highly conductive contact interfaces there is a small potential drop at the metal-semiconductor boundary[17].

If the trigger laser energy is delivered to the surface of the PCSS in bright, narrow lines, then the filaments that form will be located at the lines (figure 9). The filaments apparently grow in diameter from the photo-carriers to a diameter and resistance that balances the circuit at the lock-on voltage. Current sharing depends on the uniformity of the lines of light. This approach also yields the fastest risetime and the shortest delay between the optical pulse and PCSS switch closing. The risetime and delay of linearly triggered filaments are independent of switch gap length. This is consistent with the filaments only growing in diameter as the current rises from 10-90% of the full value, because no time is required for the filaments to grow across the insulating gap..

The optical trigger energy required to trigger linear filaments is proportional to the length of the filament, but can still be smaller than spot triggering, if the optical lines are only a few microns wide and very bright. Linear filaments have been triggered on 2.5 mm long PCSS gaps using only 100 nJ of light. Edge emitting lasers make a

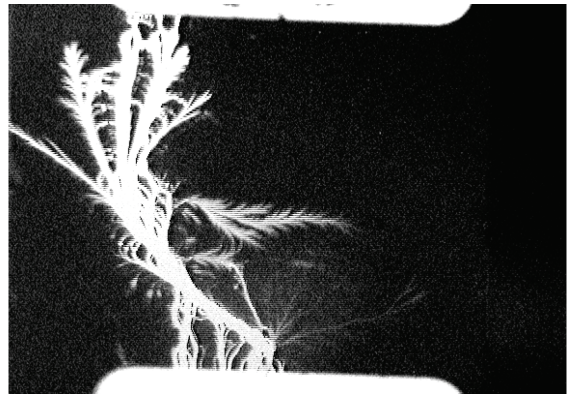

Figure 6. An image of a "bundle" of current filaments triggered with a 5 mm spot of light near the bottom center region of the 1 cm long gap in a GaAs PCSS. The voltage was about 50 kV and the current is in figure 8.

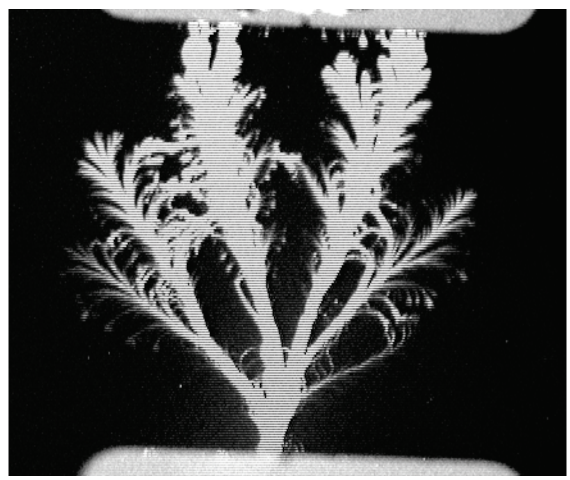

Figure 7. An image of another filament triggered under the same conditions as in the previous figure.

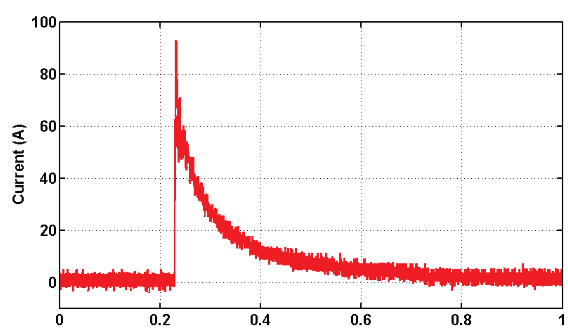

Figure 8. The current conducted by the filaments shown in the previous 2 figures.

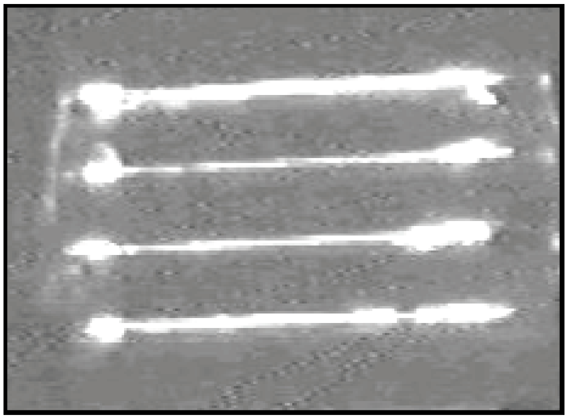

Figure 9. Current sharing, linear filaments triggered with 4, stacked, edge-emitting semiconductor lasers. The PCSS insulating gap was 5 mm and the filaments are ~1 mm apart. Switching parameters were 28kV and 30 A.

very good source for linear triggers, because the emitting region of the laser edge is only ~ 1 micron wide (a P-N junction). However, the stacking process is not monolithic and the yields for uniformly emitting lasers decrease rapidly with the number of lasers in the stack. Stacks must be tested and selected for sufficient uniformity to trigger current sharing, linear filaments.

An estimate of the carrier density required to trigger linear filaments can be obtained by using results from edge-emitting laser triggered PCSS. The carrier density, n, is approximately given by the number of photons (E/E_{ph}=100nJ/1.55eV), the quantum efficiency (q~.9), the reflectivity (R~.3), the recombination time (τ=1-10 ns), the laser pulse width (T=5 ns), and the volume in which the photons are absorbed (lwd, where d=0.2-10 μm is the absorption depth, l=2.5 mm is the line length, and w=10 μm is the line width):

$$n = (E/E_{ph})\, q\, (1-R)\, (1-e^{(-\tau/T)}) / (lwd) \qquad (1)$$

The extremes for the values and ranges listed above give $n=2\times10^{17}$-5×10^{19} cm^{-3}. The range in recombination time covers typical high resistivity GaAs (Cr-doped to EL2 compensated). The range in absorption depth represents the uncertainty caused by non-linear absorption at these high intensities. These estimates would also be somewhat lower, if carrier-carrier scattering was taken into account, which can be significant at these carrier densities.

V. OPTICAL DELIVERY SYSTEMS

There are many potential ways to create current sharing, linear filaments. Some of the ideas, that have been considered, are listed in table II, where they are ordered by the type of light source followed by the optical components. Listed next to each approach are issues that need consideration.

Table II. Potential Optical Delivery Systems

A. Single laser
    1. Line-of-sight optics – clear, stable, straight path
        a) Uniform, parallel beam that can focus to a point
        b) Cylindrical lens array
        c) Diffractive optics – extinction ratio, uniformity, many devices
            (1) Multiple order diffraction grating for monochromatic beam
            (2) Spectrum of wide-band ultra-short pulse beam
        d) Faceted Mirrors and beam splitters
    2. Fiber optics – maintain brightness with narrow lines
        a) Single mode – packing fraction
        b) Multi-mode – brightness and spot size
        c) Convert from spots to lines or dashed lines
            (1) Mini cylindrical lenses
            (2) Tapered fibers
            (3) Edge-emitting fibers
B. Multiple lasers
    1. One laser per bank – laser synchronization
    2. One laser per filament
        a) Edge-emitting lasers – uniformity and alignment
        b) VCSELS – linear VCSELS lase non-uniformly
    3. Many lasers per filament - Fiber lasers – synchronization
        a) VCSELS – energy per laser
        b) Fiber lasers – synchronization & cost
C. Uniform illumination with patterned substrates
    1. Masks to block the light between the desired locations
    2. Doped/implanted low mobility regions to limit filament growth between the desired locations
    3. Issues
        a) Lost light between filaments
        b) Depth of the process is small compared to filament diameters

For large pulsed power systems, the most efficient way to generate the optical triggers may be with a single solid state laser. This eliminates the possibility of jitter between multiple lasers, and a line-of sight system based on a solid state laser can focus to a diffraction-limited line width of a few microns using cylindrical lenses. For rugged, portable systems the flexibility and reliability of a fiber-optic delivery system may be desired. One problem with single mode fibers is injecting light into a bundle of them, due to their thick cladding. Multimode fibers have a much better packing fraction, but they cannot be focused as tightly as single mode fibers.

At the other extreme, using one or more semiconductor lasers per filament would be an excellent approach, if the lasing uniformity could be maintained to assure current-sharing Vertical cavity surface emitting lasers (VCSELs) are a promising monolithic technology, which can produce thousands of lasers per wafer. Unlike edge-emitting semiconductor lasers, VCSELs emit light perpendicular to the wafer surface, so they can be designed to emit arrays of lines of light to meet the needs of any size PCSS. Unfortunately, VCSELS have much shorter cavities than edge-emitting lasers and the development of VCSELS with sufficient intensity and uniformity to trigger current-sharing, linear filaments has been slow. To date, two parallel filaments have been triggered with VCSELS emitting dashed lines to improve their uniformity [18].

The simplest approach to triggering current-sharing, linear filaments was mentioned in the introduction. Patterned switches that block the light or inhibit filament growth between the filaments may produce reliable long-lived devices. There may be an issue with doping or ion implantation not being deep enough to stop the filaments from growing below the inhibiting surface layers. These techniques will require greater optical trigger energy, because the light that hits the absorbing or inhibiting pattern will be wasted. A combination of patterned switches with an optical delivery system that concentrates the light on the filaments may produce reliable current sharing, linear filaments and reduce the optical trigger energy substantially.

We are presently testing two approaches: (1) single solid state laser with line-of-sight optics using cylindrical micro lens arrays and (2) optically opaque masks to block the light between the filaments. The first was selected for precision focusing as a technique that will be very energy efficient. The second was selected for its simplicity. Low and high current testing with these approaches will be described in the following sections.

VI. LOW CURRENT TESTING

A low current test bed was setup to test the relative merits of optical delivery systems. The voltage and current waveforms for a typical 2.5 mm long PCSS are shown in figures 10 and 11. With this system, single filament triggering was tested with spherical and cylindrical lenses, and multiple filament triggering was tested with a cylindrical lens stack, a glass micro lens array, a plastic micro lens array, and masked switches.

A picture of multiple filament triggering through a plastic micro lens array is in figure 12. The multiple filaments are difficult to see for two reasons. First the filaments shared the current, which in this system was only 16 A peak (figure 11). Second, the image had to be recorded through the micro lens array due to its short focal length. Only a small angle dependent region of the lens transmits light from the filaments. Viewing the lens at a range of angles shows relative uniform light emitted over most of the insulating gap. Efficient high gain PCSS voltage and current waveforms were also observed during these measurements.

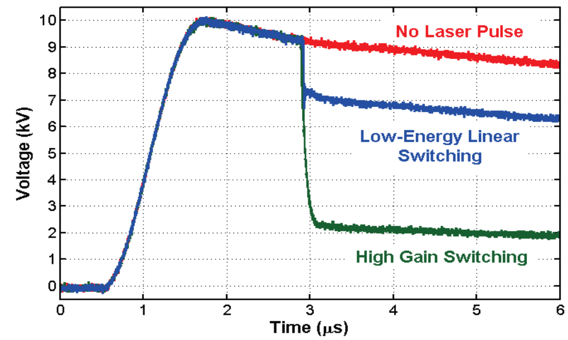

Figure 10. Pulse charging waveforms show PCSS voltage for no (top), linear (middle), and high gain (bottom) switching in the low current circuit. Too much trigger energy for high gain produces weak linear switching.

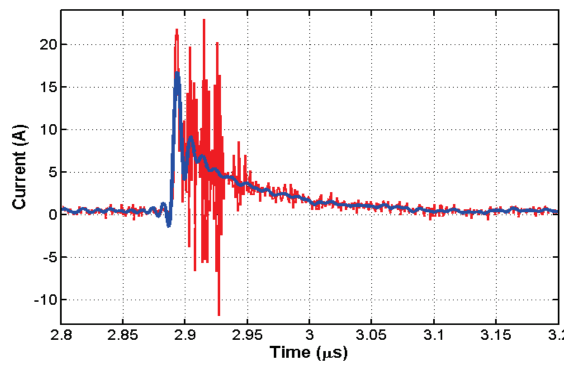

Figure 11. The PCSS current produced in the low current circuit. An extremely noisy signal due to the high band-width of the PCSS picked up by the current viewing resistor is filtered for a more accurate representation.

Figure 13 shows a masked PCSS that is being triggered with uniform illumination. The filaments are easier to observe through the mask than the micro lens array, but part of the true diameter and interaction of the filaments may be hidden by the mask. As above, the recombination light is weak because the filaments share only 16A.

VII. HIGH CURRENT MULTIPLE FILAMENT TESTING

The high current test bed was designed with the capability of pulse charging a 40 Ω, 10 ns, oil-filled Blumlein at up to 100 kV. The goal is to trigger 100 filaments and switch 2.5-3.0 kA with three 1 cm square PCSS. A low current circuit is also required to test the PCSS while the optical delivery system is being aligned and optimized. If a misaligned trigger system only triggers a few filaments instead of the desired 100, the current in the triggered filaments would be too high and would damage the PCSS. Since the impedance of a

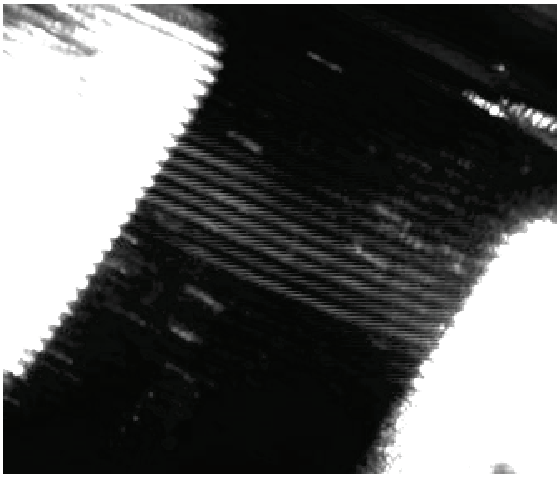

Figure 12. Multiple filament triggering with a plastic micro lens array. The 2.5 mm PCSS was recorded through the lens.

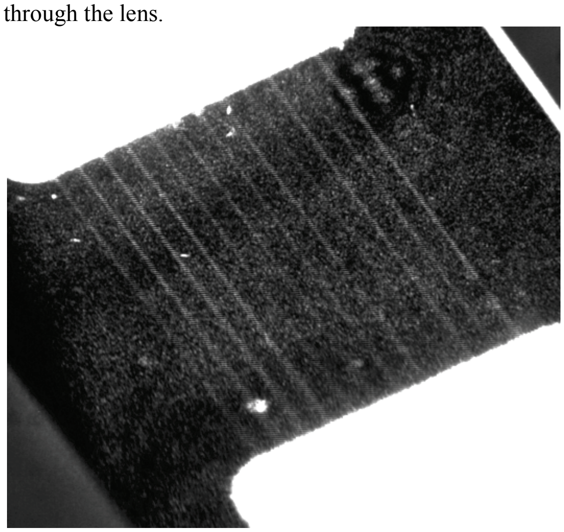

Figure 13. Uniform illumination of a masked 2.5 mm gap PCSS shows light being emitted from all of the lines.

Blumlein is not easily adjustable, a second current limited capacitive discharge circuit was assembled for setting up the PCSS and optimizing the optical delivery system. The switch mount on the second system looks like the end of a Blumlein, to imitate the fields around the PCSS, however it is only a few inches long and derives its energy from a capacitor with discharge current limited by an appropriate resistor.

Pictures of the two circuits are shown in figure 14. With the low current circuit charged to 50 kV, the PCSS will switch 80 A in an exponential decay of about 50 ns. With the high current system charged to 60 kV, the PCSS will switch 2.7 kA for 10 ns (flat topped). The Blumleins are suspended from an oil tank lid so the entire circuit can be lowered into the oil for testing and raised above the oil for easy access. Part of the optical delivery system is also suspended from the lid (figure 15) so that the alignment, except for final adjustments is maintained above or below the oil. A Lucite box is used to displace the oil so the beam path can have normal incidence on the PCSS and minimal path length through the oil.

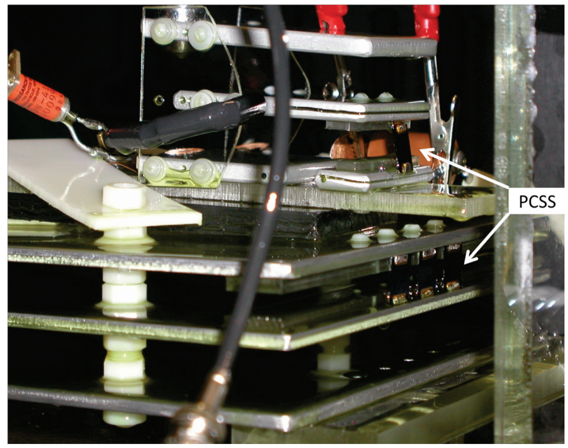

Figure 14. High and low current test fixtures are shown here. One PCSS is mounted in the "short Blumlein" (top) and three PCSS are on the "long Blumlein" (bottom).

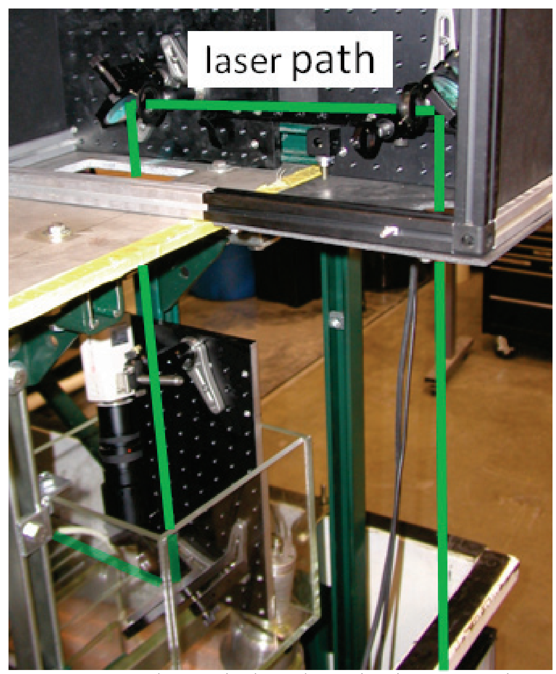

Figure 15. The optical path maintains approximate alignment as the tank lid is raised or lowered.

The filament images shown in figures 6 and 7 and the PCSS current shown in figure 8 are from a spot triggered filament in the low current ("short Blumlein") test circuit. To date we have not tested a PCSS in the high current ("long Blumlein") test circuit. We are presently aligning the plastic micro lens array onto a single PCSS in the low current test circuit.

VIII. CONCLUSION

High gain GaAs PCSS are promising pulsed power switches due to their low energy optical triggering requirement. Considering all the demonstrated switching properties shown in section III, high current is the "missing link" for practical, reliable, scalable PCSS in large pulsed power applications. Since high gain switching produces current filaments that must be limited in amplitude and duration to avoid damage, multiple, current sharing, linear filaments are the answer to high current, high gain, GaAs PCSS. The problem is essentially reduced to selecting and designing the appropriate optical delivery system. We are in the process of testing two types of modular optical delivery systems to trigger multiple, current-sharing, linear filaments: line-of-sight micro lens arrays and uniformly illuminated masked PCSS.

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